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10th Nuclear Science Training Course with NUCLEONICA
Institute of Nuclear Science of Ege University,
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Nuclear Fuel Cycle and WebKOrigen

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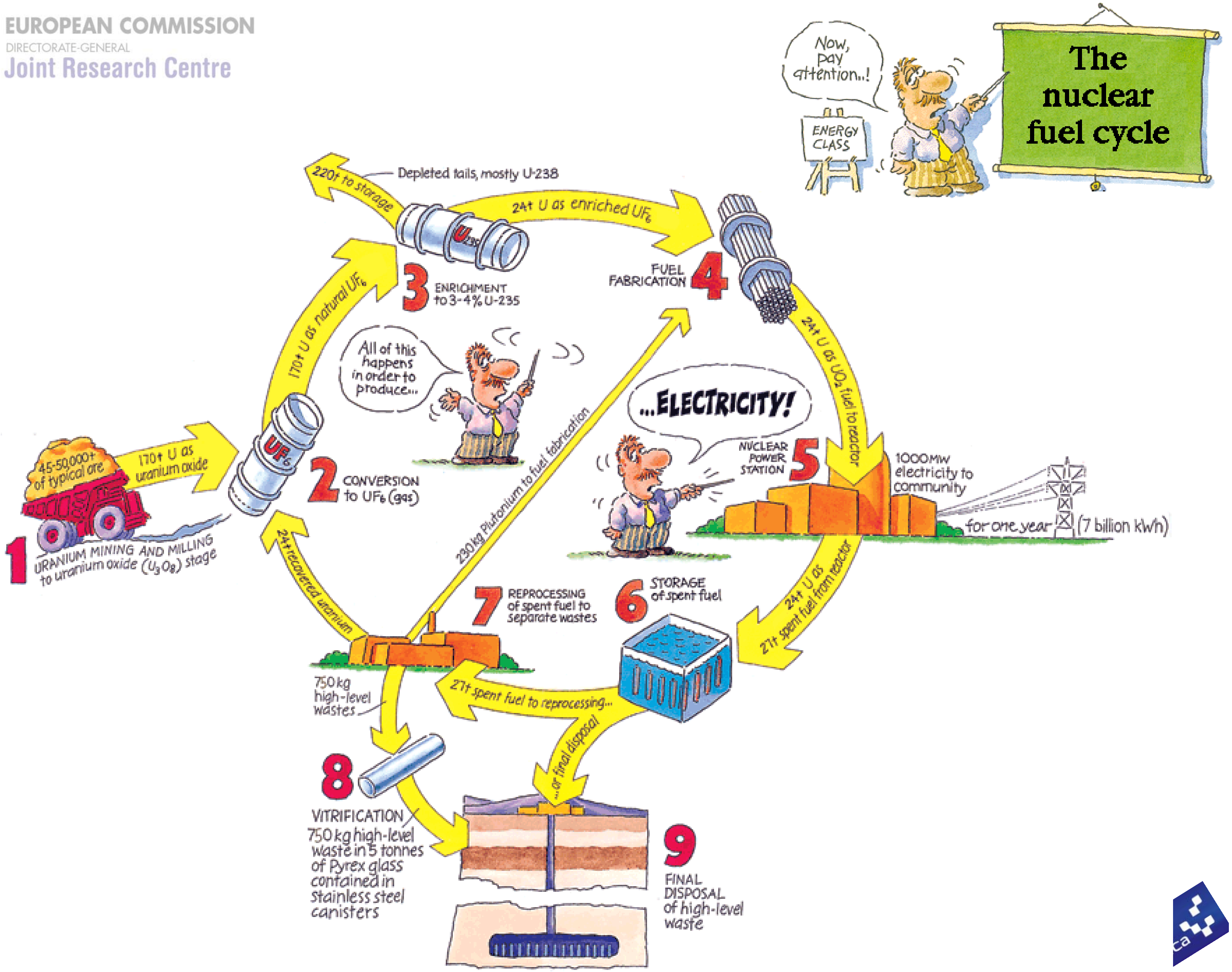

Now, pay attention..!
ENERGY CLASS
The nuclear fuel cycle
45-50,000t of typical ore
170t U as uranium oxide
1 URANIUM MINING AND MILLING to uranium oxide (U_3O_8) stage
2 CONVERSION to UF_6 (gas)
170t U as natural UF_6
220t to storage
Depleted tails, mostly U-238
3 ENRICHMENT to 3-4% U-235
24t U as enriched UF_6
4 FUEL FABRICATION
24t U as UO_2 fuel to reactor
All of this happens in order to produce...
...ELECTRICITY!
5 NUCLEAR POWER STATION
1000MW electricity to community
for one year (7 billion kWh)
24t U as 27t spent fuel from reactor
6 STORAGE of spent fuel
27t spent fuel to reprocessing...
...or final disposal
7 REPROCESSING of spent fuel to separate wastes
230kg Plutonium to fuel fabrication
24t recovered uranium
750 kg high-level wastes
8 VITRIFICATION 750 kg high-level waste in 5 tonnes of Pyrex glass contained in stainless steel canisters
9 FINAL DISPOSAL of high-level waste

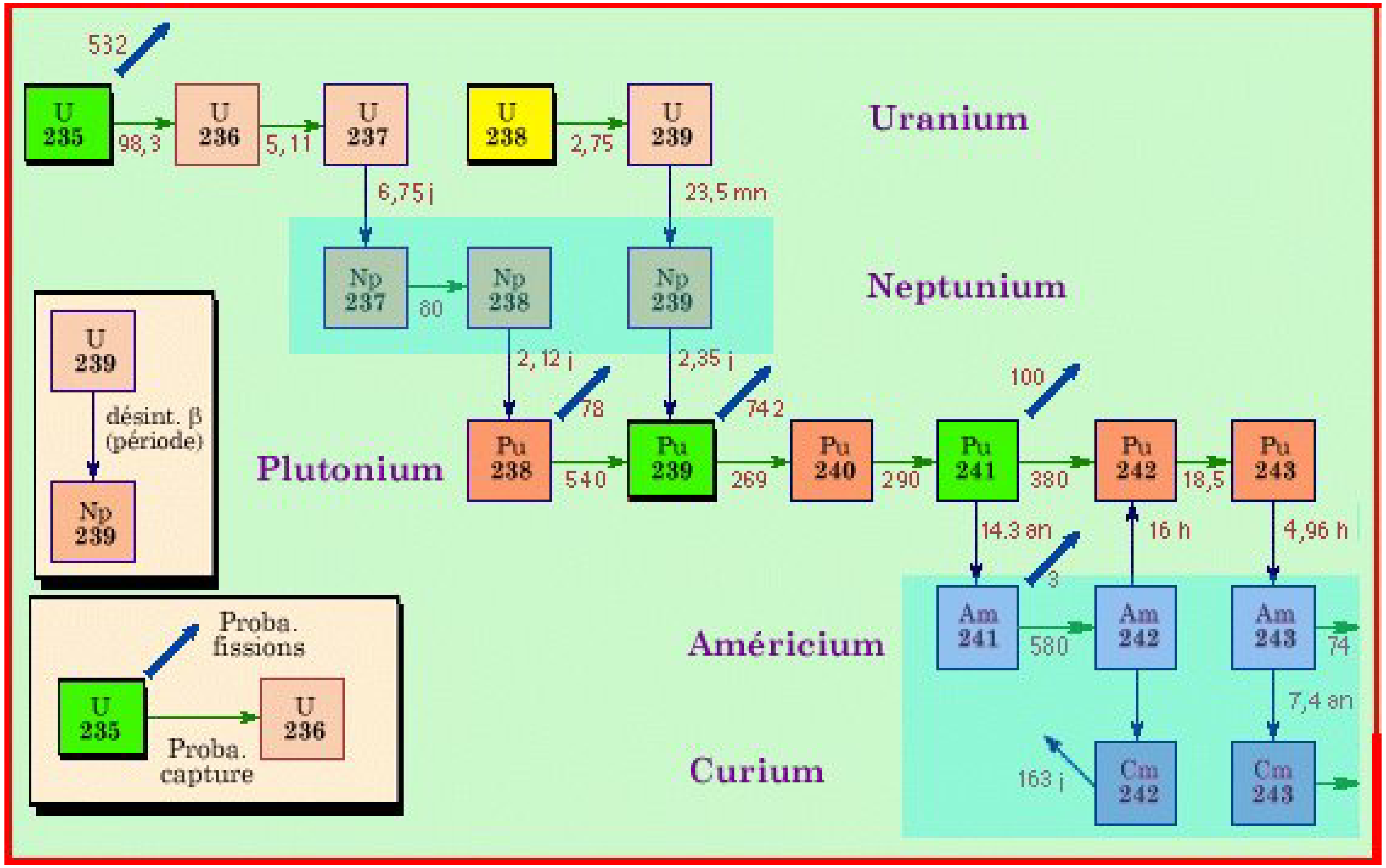
Fuel utilization

- The central purpose of the fuel cycle is the consumption of fuel in the reactor and extraction of energy.
- An overall measure of the energy obtained from the fuel is its *burn-up*, i.e. the energy per unit of mass of fuel (megaywatt-days or gigawatt-days of thermal output per ton of initial heavy metal)
- In U-fuel reactors, most of the energy comes from the fission of ^{235}U. However production of the ^{239}Pu plays a significant role in the energy economy of the reactor.

Actinide production in a reactor

- Generated by neutron capture not followed by fission
- The actinide produced with greater abundance is the plutonium (its principal isotope is plutonium-239, fissile material). However, reactors generate other actinides called "minor actinides". Main ones are neptunium-237, américium-241 et 243 and curium-244 et 245. The minor actinides represent with the plutonium the major part of the high activity and long lived nuclear waste.
- The transuranium actinides (Z>92) don't exist in natural state, their isotopes present often a short half-life with exception of some isotopes of Np, Pu, Am et Cm produced in ponderable quantity in nuclear reactor.

Actinides Production



Decay vs. Production

- In a reactor, the population of an actinide is driven by:

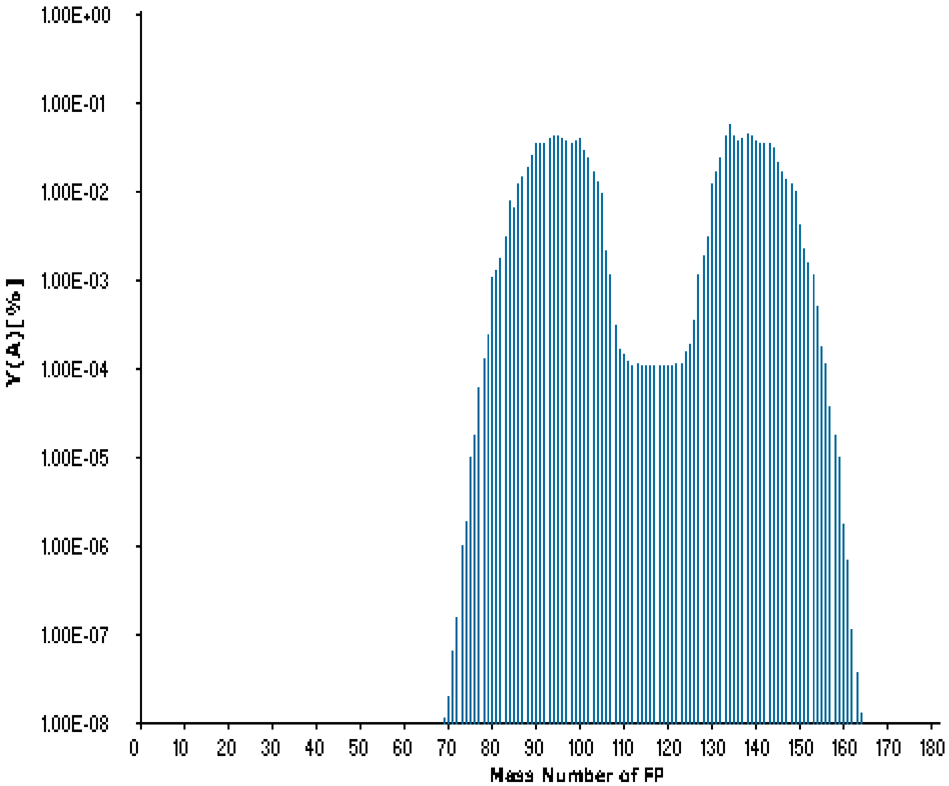
$$\frac{dN(t)}{dt} = -\lambda N - \sigma_a N\Phi = -\left(\frac{\ln 2}{\tau} + \frac{\ln 2}{\tau_{bo}}\right)N$$

with $\sigma_a = \sigma_{n,\gamma} + \sigma_{n,\,fission}$

- if $\tau >> \tau_{bo}$ decay neglectible
- if $\tau << \tau_{bo}$ nuclear reaction neglectible
- if $\tau \sim \tau_{bo}$ a small flux change can make vary the nuclide behavior

Fission products

- Asymmetrical fission
- Isotopes of more than 30 elements are observed as fission products
- Most of the fragments are far of the stability and then decay by β^- or delayed neutron



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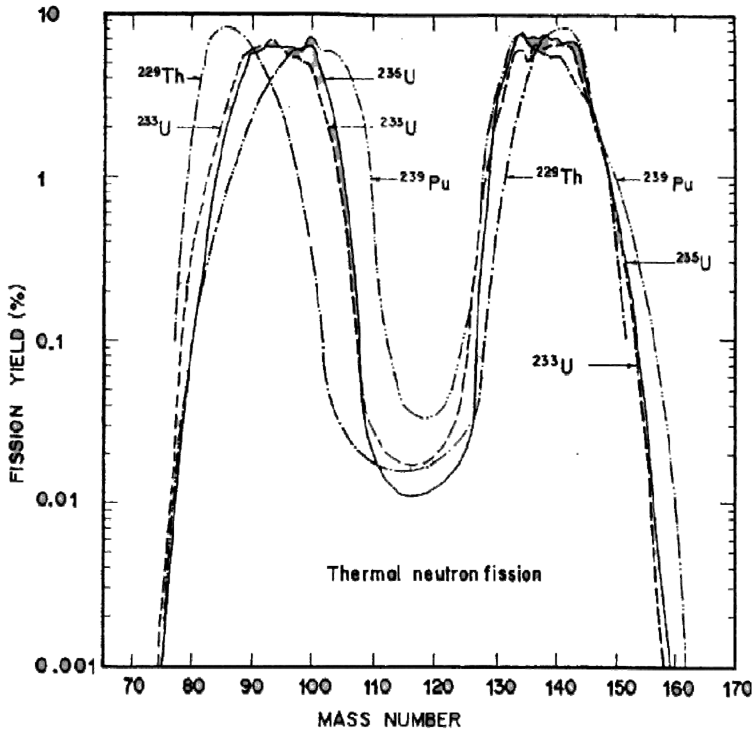
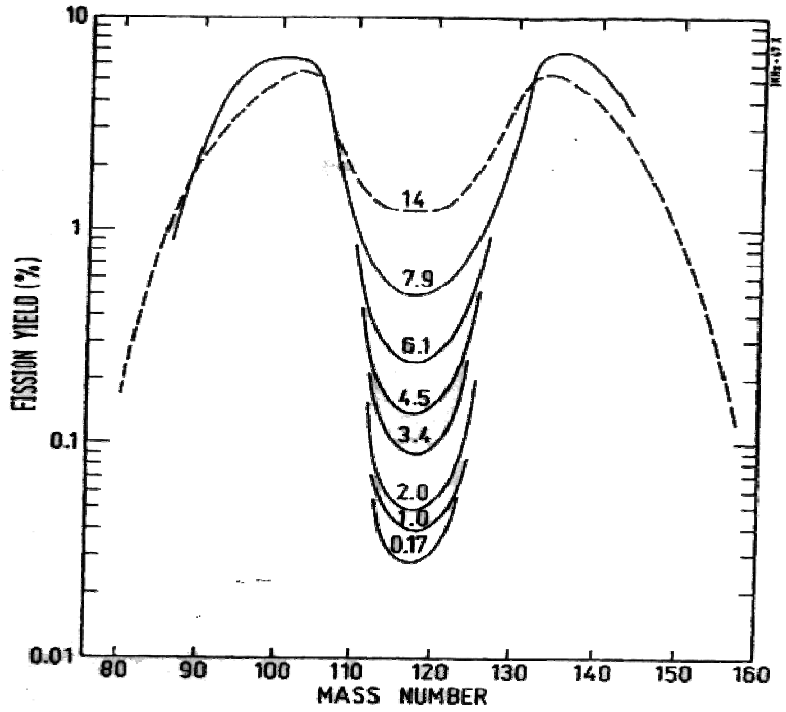
Dependence of the FY distribution in n-energy and target nature





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nucleonica

Short-lived fission products

- *(betwen 5 and 100 years) – to be compared with time spent in fuel in the reactor ~ 3 years*
  - Short half-life: most of them will decay to stable daughters
  - HL ~ year: accumulation in fuel
  - Ex: ^{135}Xe (8 h) neutron poison, ^{131}I (8 days) mobile and volatile
  - Average HL: the most problematic ^{137}Cs (30 y) and ^{90}Sr (28 y). They represent the principal source of contamination at medium term due to Tchernobyl and atomic bomb tries
  - The fission products represent almost the whole radioactivity of freshly discharged fuel

Long-lived fission products

- *T > 100 ans*

- Greater is the half-life and less radioactive is the nuclide→ problem: half-lives are from 30 y to millions of years
- After ~500 y, 1/1000 of the actinide activity remains
- Only a few hand of long-lived FPs: ^{99}Tc (3,1x10^{5} y), ^{135}Cs(2,3x10^{6} y), ^{129}I (1,57x10^{7} y), ^{107}Pd (6,5x10^{6} y), ^{93}Zr (1,5x10^{6} y)
- ^{129}I et ^{135}Cs can propagate in the environment and are volatile
- ^{129}I is 240 million times less hazardous than ^{131}I (short-lived)
- ^{135}Cs is 77000 times less hazardous than ^{137}Cs (short-lived)
- ^{99}Tc et ^{135}Cs are difficult to transmute

Back end of the fuel cycle

- Periodically a portion of the fuel is removed and replaced by fresh fuel (typically 1/3 replaced yearly)
- Disposal (permanent or retrievable) & Reprocessing (U/Pu, some of the fission products)

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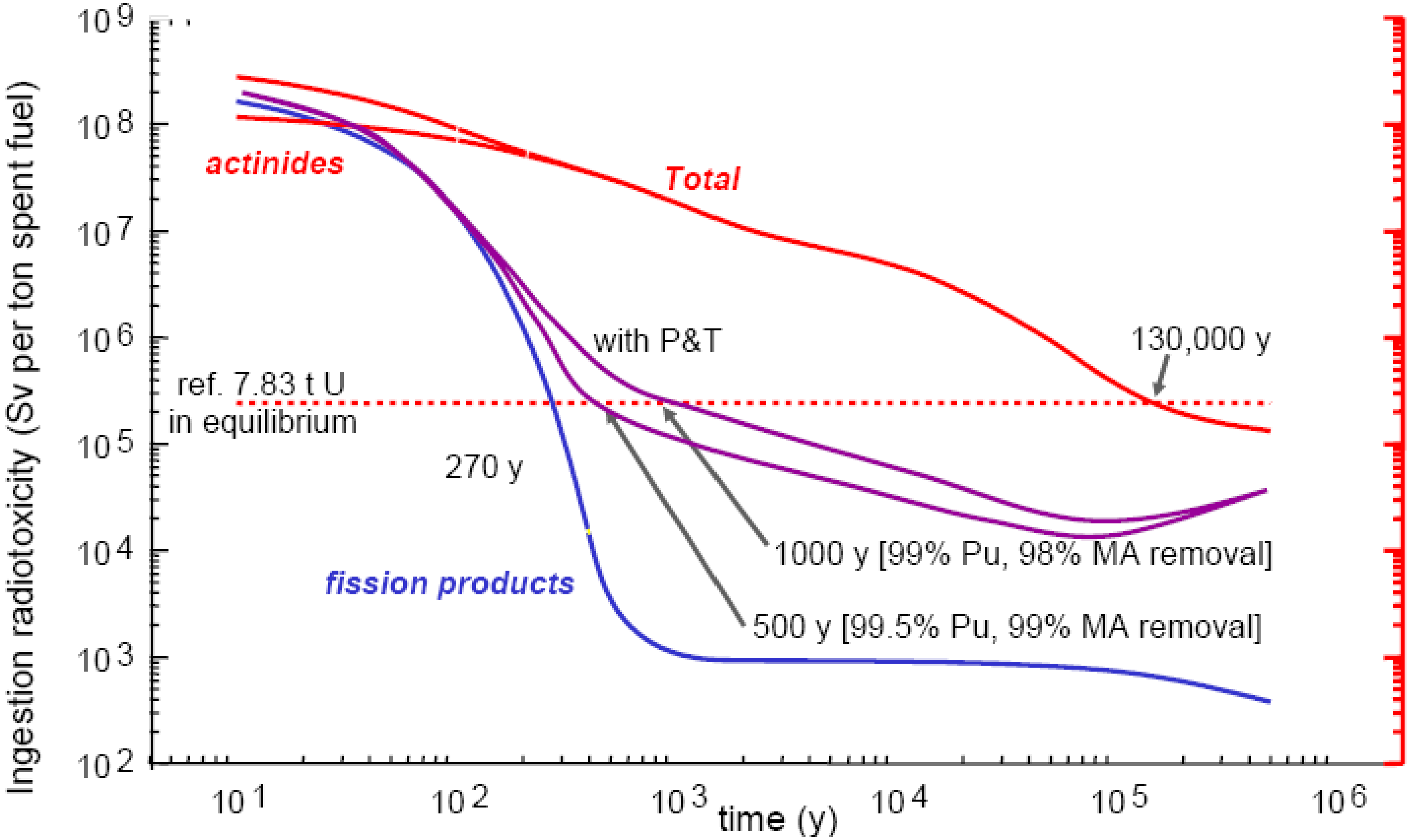
Ingestion Radiotoxicity



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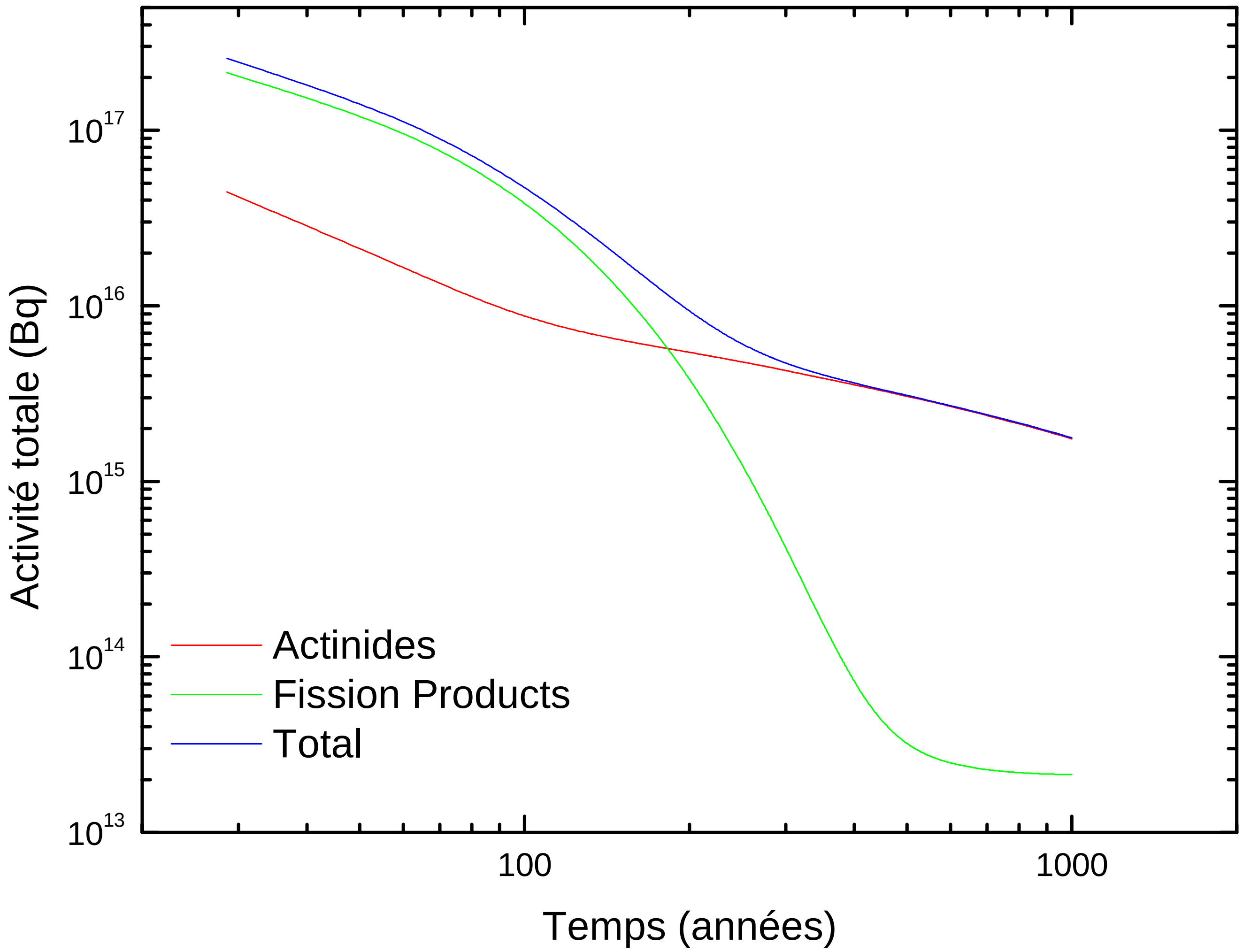
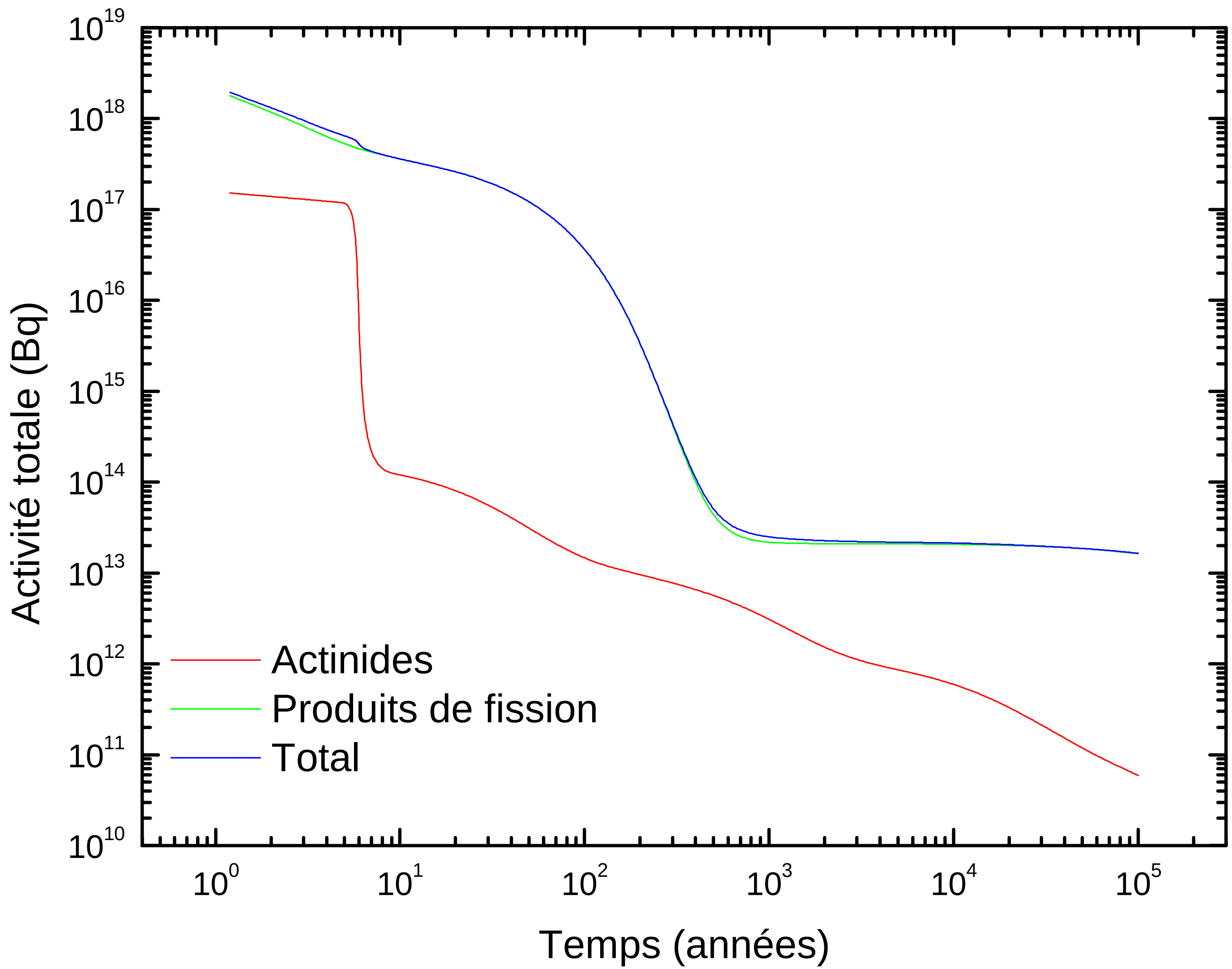
Actinide vs. Fission Products Activity



REP, UOX 4%, 55 MWd/kg 20 t HM, 5x1a, 80%

…with reprocessing



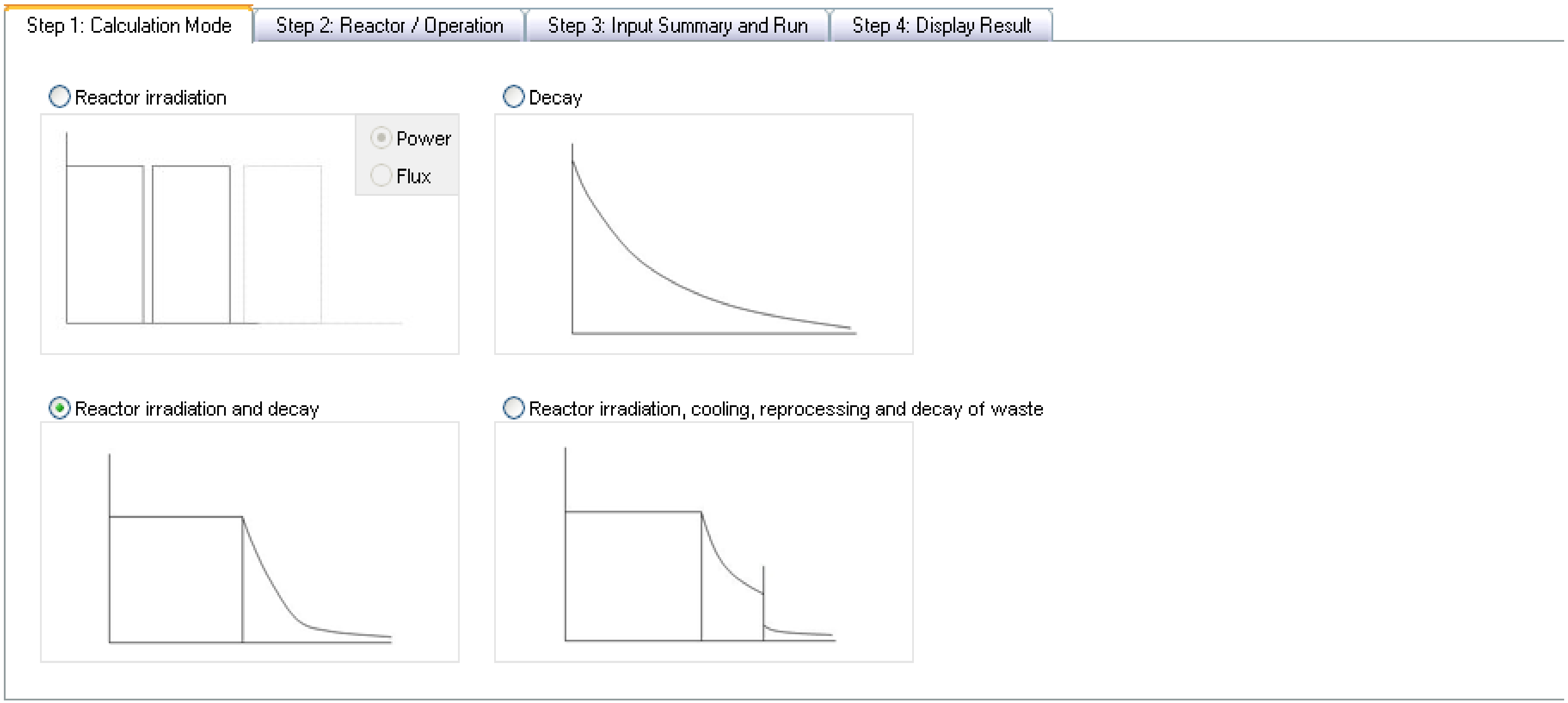
REP, UOX 4%, 55 MWd/kg 20 t HM, 5x1a, 80%

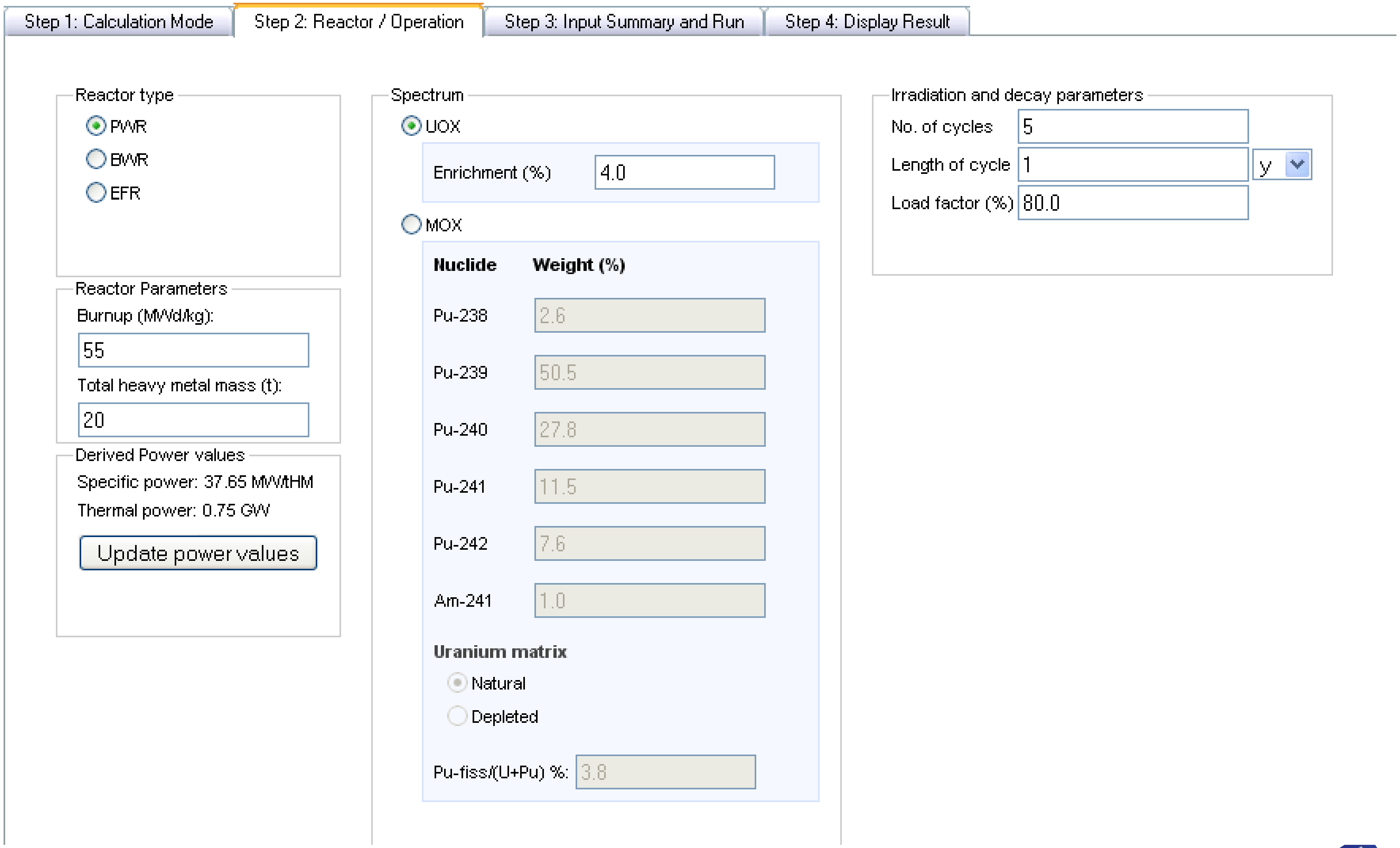
Web-KOrigen

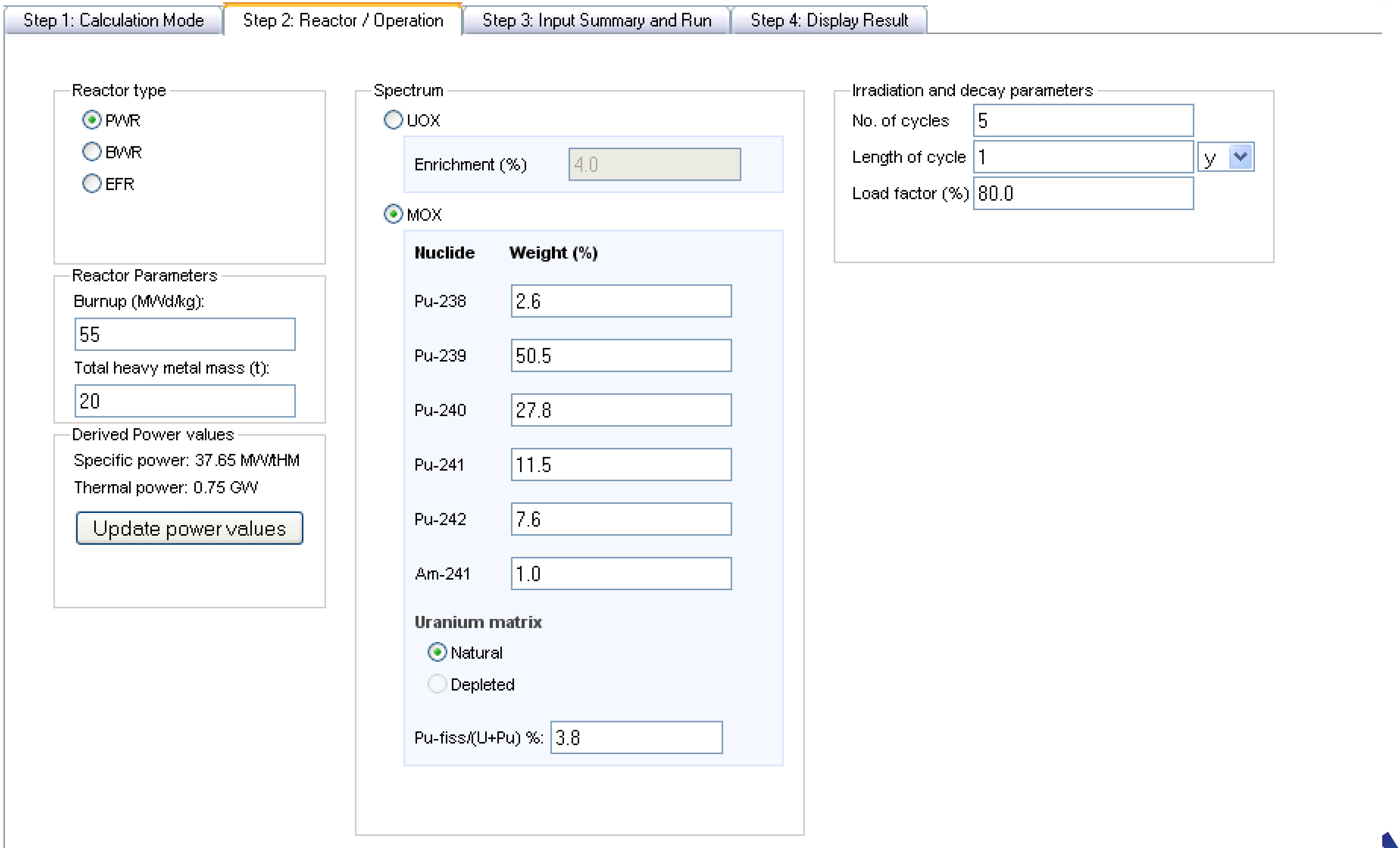
- Research Centre Karlsruhe together with the Nucleonica developers form the European Commission's Joint Centre have created an extended version of KORIGEN called webKORIGEN
- It supports calculations for a set of standardized problems, trimmed to three major classes of nuclear plants whereas more complex and general tasks can be solved only with the KORIGEN original code
- The nuclear systems supported by webKORIGEN are: the thermal power plants deployed worldwide as ***Pressurized Water Reactors*** (PWR) and ***Boiling Water Reactors*** (BWR)and a future extension to the current industrial technology : the ***European Fast Reactor*** (EFR).
- In webKORIGEN four operational modes can be run. They constitute only a subset of full variety of KORIGEN features, dedicated data libraries and miscellaneous options. The modes are depicted as diagrams versus time: fuel power history versus irradiation time, decay heat or decreasing mass concentration versus decay time.

webKORIGEN

webKORIGEN was developed from the Oak Ridge Isotope Generation and Depletion code ORIGEN. Starting with a given initial reactor fuel or a single target nuclide, it calculates the time evolution of nuclide densities changing due to decays and neutron-induced reactions, and determines derived nuclear properties such as masses, radioactivities, heat releases, radiotoxicities, emission of radiation, etc...




Step 1: Calculation Mode
Step 2: Reactor / Operation
Step 3: Input Summary and Run
Step 4: Display Result
Reactor type
PWR
BWR
EFR
Reactor Parameters
Burnup (MWd/kg):
55
Total heavy metal mass (t):
20
Derived Power values
Specific power: 37.65 MW/tHM
Thermal power: 0.75 GW
Update power values
Spectrum
UOX
Enrichment (%)
4.0
MOX
Nuclide
Weight (%)
Pu-238
2.6
Pu-239
50.5
Pu-240
27.8
Pu-241
11.5
Pu-242
7.6
Am-241
1.0
Uranium matrix
Natural
Depleted
Pu-fiss/(U+Pu) %:
3.8
Irradiation and decay parameters
No. of cycles
5
Length of cycle
1
y
Load factor (%)
80.0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Reactor type
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BWR
EFR
Reactor Parameters
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Derived Power values
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Thermal power: 0.75 GW
Update power values
Spectrum
UOX
Enrichment (%)
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Weight (%)
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Pu-239
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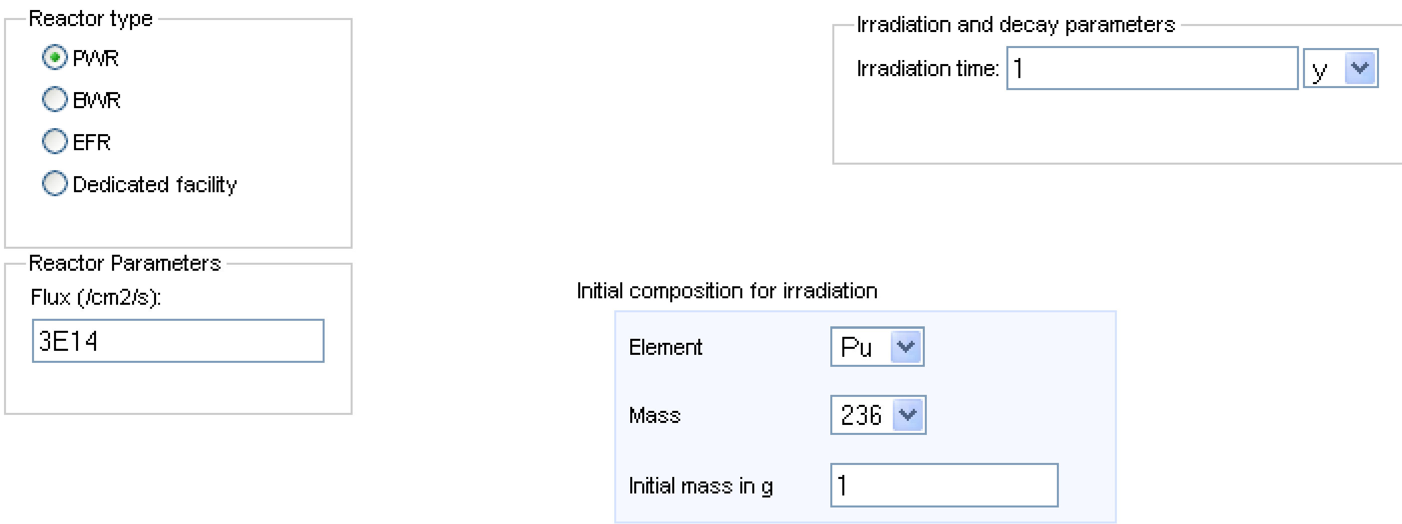
Pu-240
27.8
Pu-241
11.5
Pu-242
7.6
Am-241
1.0
Uranium matrix
Natural
Depleted
Pu-fiss/(U+Pu) %:
3.8
Irradiation and decay parameters
No. of cycles
5
Length of cycle
1
y
Load factor (%)
80.0


Reactor type
PWR
BWR
EFR
Dedicated facility
Reactor Parameters
Flux (/cm2/s):
3E14
Irradiation and decay parameters
Irradiation time: 1
y
Initial composition for irradiation
Element
Pu
Mass
236
Initial mass in g
1

Reactor type

- PWR (selected)
- BWR
- EFR

Reactor Parameters

Burnup (MWd/kg): 50

Derived Power values

Specific power: 27.38 MW/tHM

Spectrum

- UOX
  - Enrichment (%): 4.0
- MOX

Nuclide	Weight (%)
Pu-238	2.6
Pu-239	50.5
Pu-240	27.8
Pu-241	11.5
Pu-242	7.6
Am-241	1.0

Uranium matrix

- Natural (selected)
- Depleted

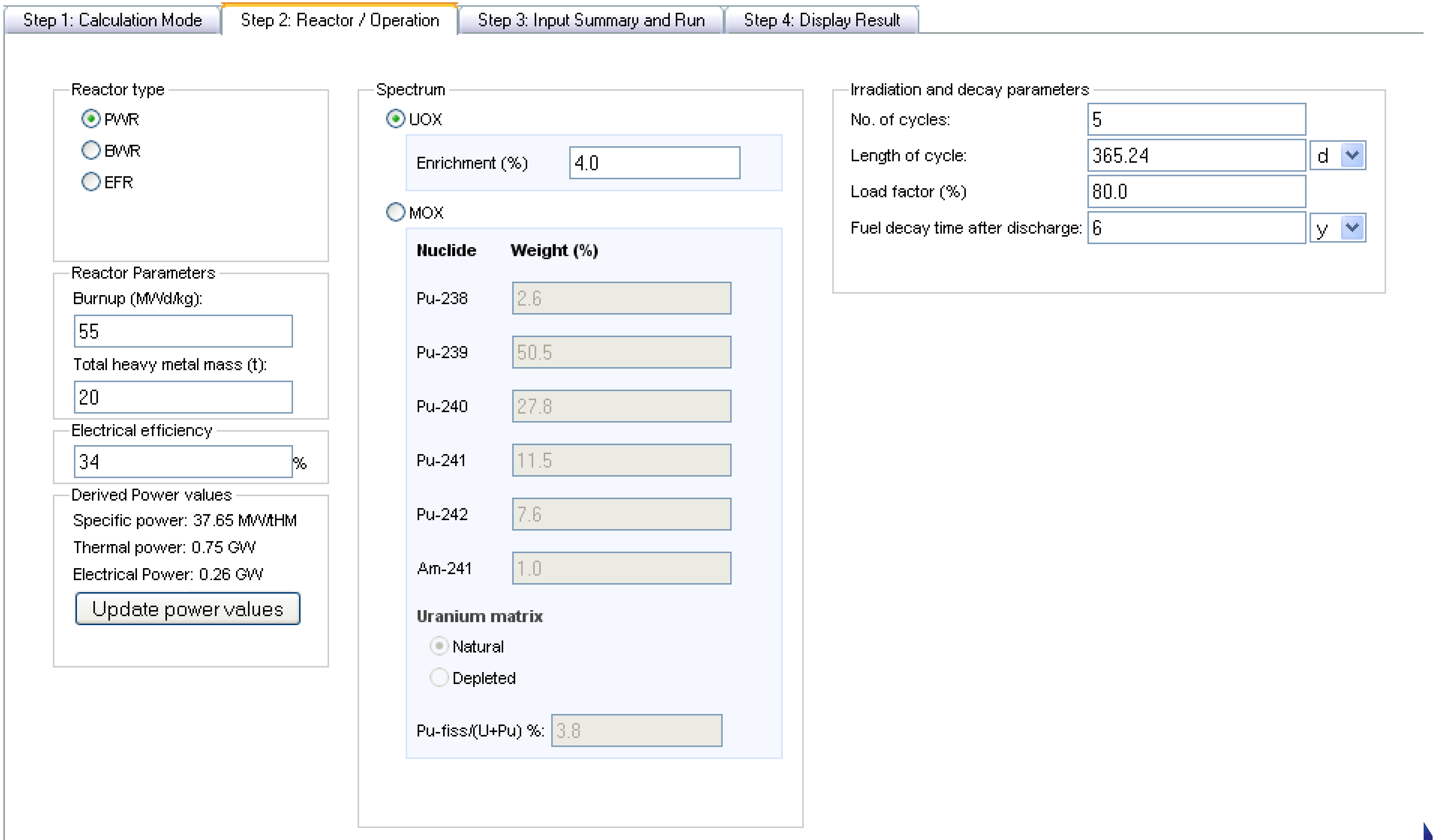
Pu-fiss/(U+Pu) %: 3.8

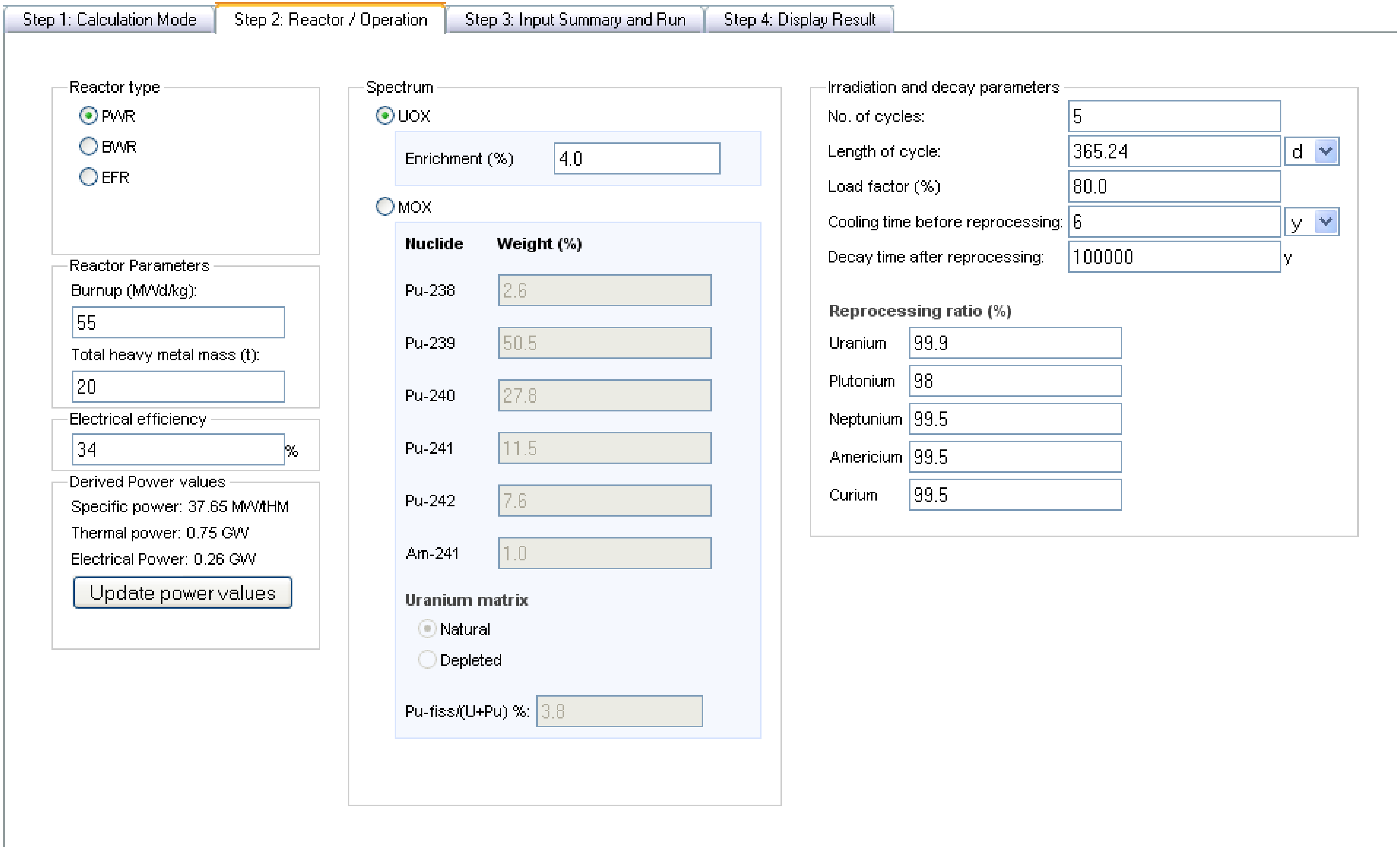
Initial nuclide for decay

Element	Pu
Mass	236
Initial mass in g	1

Irradiation and decay parameters

Decay time: 5 y


Step 1: Calculation Mode
Step 2: Reactor / Operation
Step 3: Input Summary and Run
Step 4: Display Result
Reactor type
PWR
BWR
EFR
Reactor Parameters
Burnup (MWd/kg):
55
Total heavy metal mass (t):
20
Electrical efficiency
34 %
Derived Power values
Specific power: 37.65 MW/tHM
Thermal power: 0.75 GW
Electrical Power: 0.26 GW
Update power values
Spectrum
UOX
Enrichment (%) 4.0
MOX
Nuclide Weight (%)
Pu-238 2.6
Pu-239 50.5
Pu-240 27.8
Pu-241 11.5
Pu-242 7.6
Am-241 1.0
Uranium matrix
Natural
Depleted
Pu-fiss/(U+Pu) %: 3.8
Irradiation and decay parameters
No. of cycles: 5
Length of cycle: 365.24 d
Load factor (%) 80.0
Fuel decay time after discharge: 6 y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EFR
Reactor Parameters
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55
Total heavy metal mass (t):
20
Electrical efficiency
34 %
Derived Power values
Specific power: 37.65 MW/tHM
Thermal power: 0.75 GW
Electrical Power: 0.26 GW
Update power values
Spectrum
UOX
Enrichment (%) 4.0
MOX
Nuclide Weight (%)
Pu-238 2.6
Pu-239 50.5
Pu-240 27.8
Pu-241 11.5
Pu-242 7.6
Am-241 1.0
Uranium matrix
Natural
Depleted
Pu-fiss/(U+Pu) %: 3.8
Irradiation and decay parameters
No. of cycles: 5
Length of cycle: 365.24 d
Load factor (%) 80.0
Cooling time before reprocessing: 6 y
Decay time after reprocessing: 100000 y
Reprocessing ratio (%)
Uranium 99.9
Plutonium 98
Neptunium 99.5
Americium 99.5
Curium 99.5

Results

Top Nuclides	Results
Xe136	7.741E+04
Xe134	5.047E+04
Nd144	4.689E+04
Ba138	4.382E+04
Ba137	4.247E+04
Ce140	4.242E+04
La139	4.027E+04
Ce142	3.782E+04
Pr141	3.735E+04
Xe132	3.637E+04
Cs133	3.500E+04
Mo100	3.002E+04
Mo98	2.863E+04
Zr96	2.664E+04
Ru101	2.643E+04
Mo97	2.608E+04
Zr94	2.563E+04
Mo95	2.446E+04
Nd143	2.327E+04
Zr93	2.196E+04

Top Elements	Results
Xenon	1.744E+05
Zirconium	1.319E+05
Neodymium	1.288E+05
Molybdenum	1.114E+05
Barium	9.534E+04
Cerium	8.025E+04
Ruthenium	7.913E+04
Cesium	4.708E+04
Lanthanum	4.027E+04
Praseodymium	3.735E+04
Tellurium	9.871E+03

Totals	Results
Actinides:	1.906E+04
Fission Prod.	1.126E+06
Total	1.145E+06

20 most important nuclides

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